Transverse echoes as diagnostic tools

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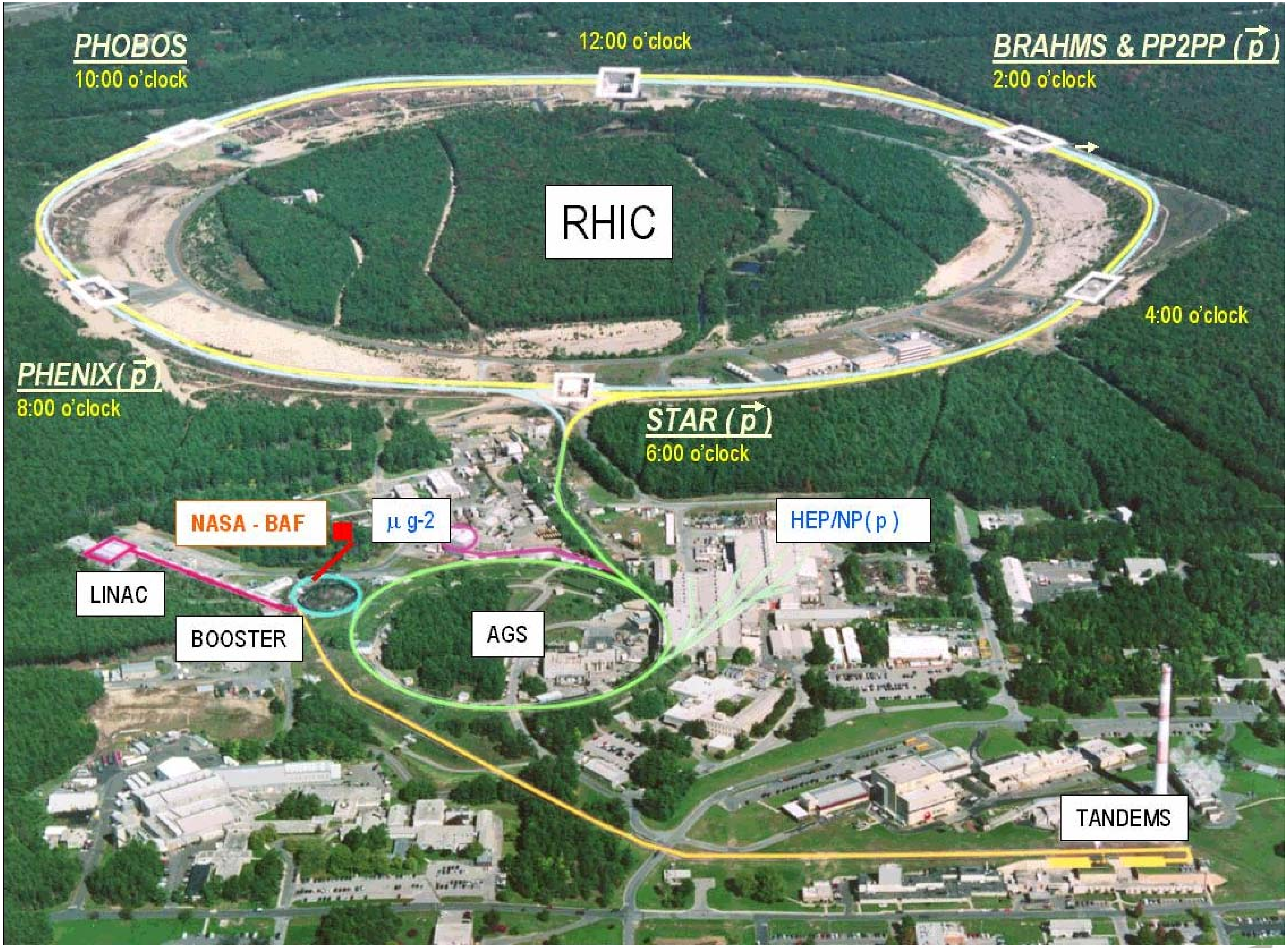
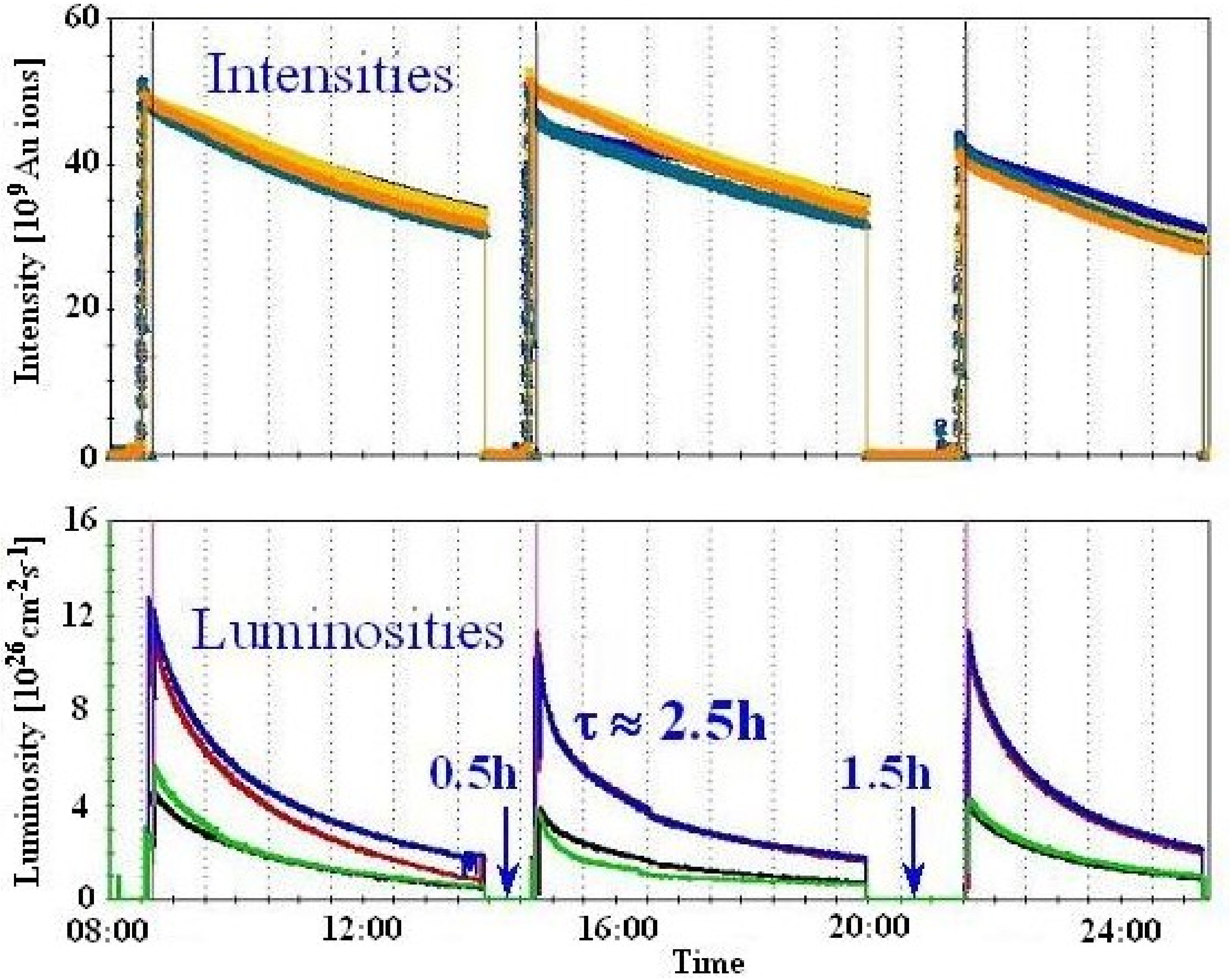
RHIC overview



Luminosity lifetime of colliding Au^{79+} beams



Motivation

- Luminosity lifetime for heavy ions dominated by IBS
  - Effort to implement stochastic cooling here: M. Brennan, M. Blaskiewicz
  - RHIC II upgrade based on e-cooling here: I. Ben-Zvi, A. Fedotov, G. Wang
- Main emittance growth mechanism working against cooling is IBS

→ Good knowledge of IBS growth rates needed to predict cooling times and equilibrium beam sizes

→ Cooling times of order 1 hour, cannot afford error larger than about factor 2

Motivation

- IBS growth rate measurements usually done by observing the free expansion of bunches
  - Must be on time scale of interest [15min at injection, hrs at store]
  - Need precise emittance measurement [not easy transversely]

- Echo measurements are
  - Much faster (~1000 turns), allow parameter scans
  - Potentially very sensitive
  - Do not rely on precise emittance measurement

Transverse echoes

- Echoes well known in plasma physics
- Sensitive method to measure diffusion rates
- Theoretical accelerator papers by
  Stupakov, Kauffmann (SSC)
- Longitudinal echos observed at
  - FNAL AA [Spenzouris, Colestock et al.]
  - CERN SPS [Brüning et al.]
  - BNL AGS [Kewisch, Brennan]

Transverse echoes – phase space simulation

US-LHC Collaboration Meeting: Accelerator Physics Experiments for Future Hadron Colliders, BNL, 2000

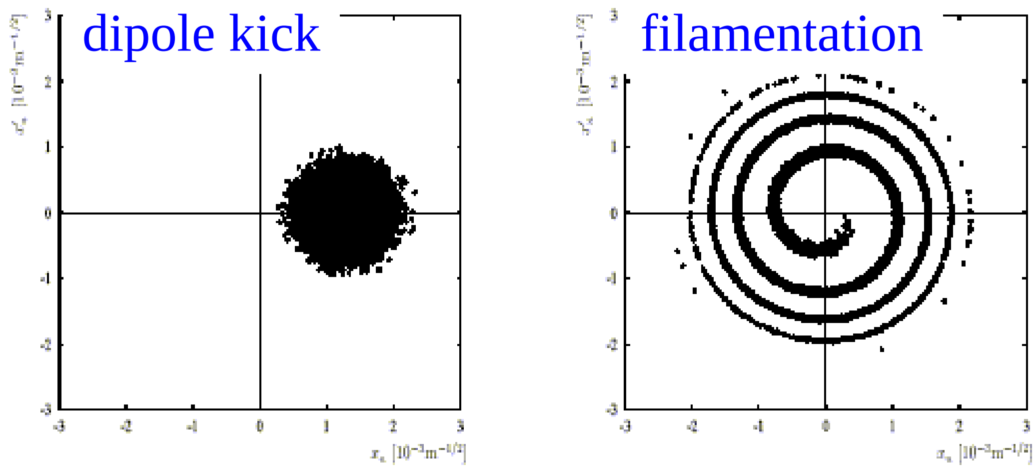


Figure 1: Left: Horizontal particle distribution in normalized phase space after the initial dipole offset. Right: The same distribution 500 turns later.

- 1-turn quadrupole kick is difficult
- echo-like signal was also observed with 2 dipole kicks of different strength (F. Ruggiero, SPS)

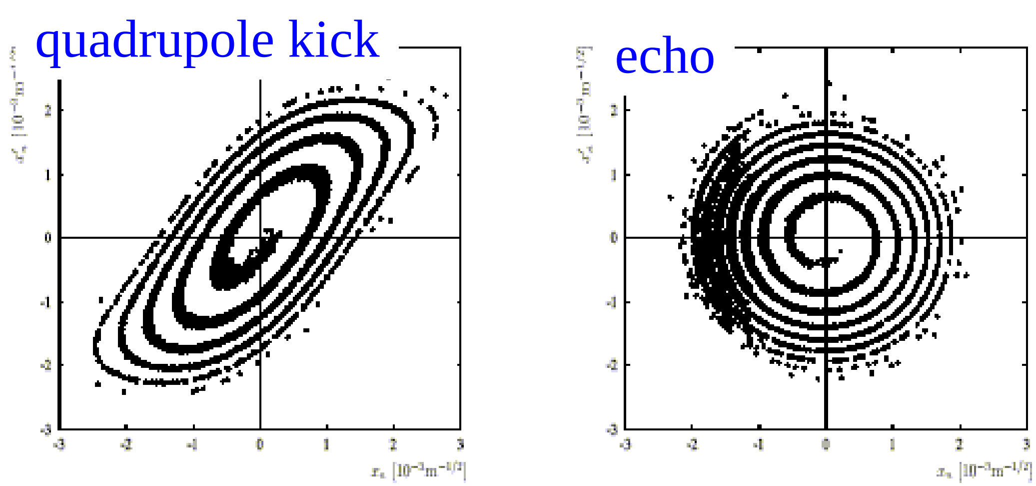


Figure 2: Left: Horizontal particle distribution in normalized phase space right after a 1 turn long quadrupole kick placed 500 turns after the dipole kick. Right: The same distribution 500 turns after the quadrupole kick.

Transverse echoes – dipole moment simulation

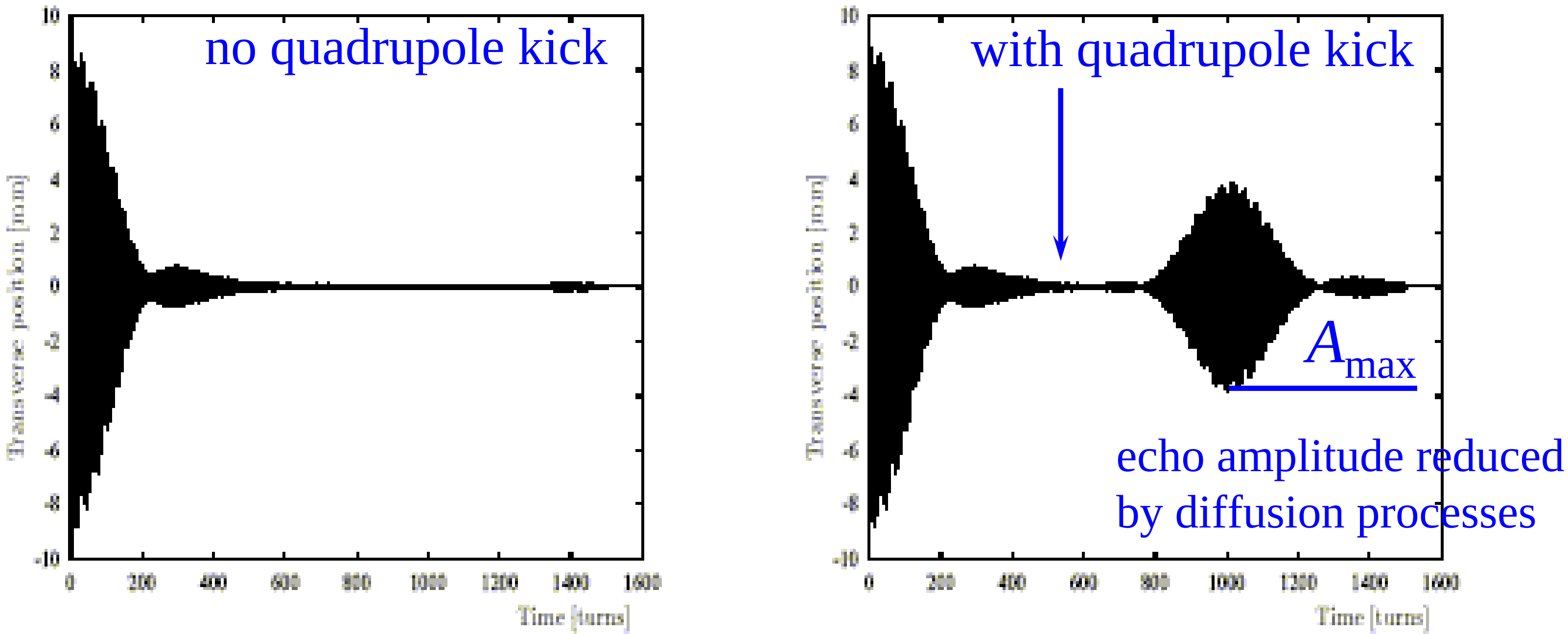


Figure 3: Left: The dipole moment of the distribution versus time after a dipole kick. Right: The same signal with an additional quadrupole kick at 500 turns after the dipole kick.

[W.Fischer, B. Parker, O. Brüning, "Transverse echos in RHIC", proceedings of the US-LHC Collaboration Meeting: Accelerator Physics Experiments for Future Hadron Colliders, BNL (2000).]

Transverse echoes – echo amplitude formulae

- Approximate echo signal for one-turn quadrupole kick, small dipole kick, constants diffusion coefficient D_0 (Stupakov, PAC97 and Handbook)

$$A_{echo} = \frac{\eta^{\max}}{a} = \frac{Q}{\tau_d}\frac{\tau}{1+8D_0\mu^2\omega_0^2\tau^3/3\varepsilon}$$

- η_{max} echo amplitude, a dipole kick,
- $Q=\beta/f$ at quad
- $\tau_{\mathrm{d}}=T_0/4\pi\mu$ decoherence time, T_0 rev. time, $\omega_0=2\pi/T_0$
- τ time between dipole and quadrupole kick
- μ detuning (ΔQ at 1σ amplitude), ε distribution rms
- D_0 diffusion coefficient

→ not applicable for RHIC experiments (due to parameter range)

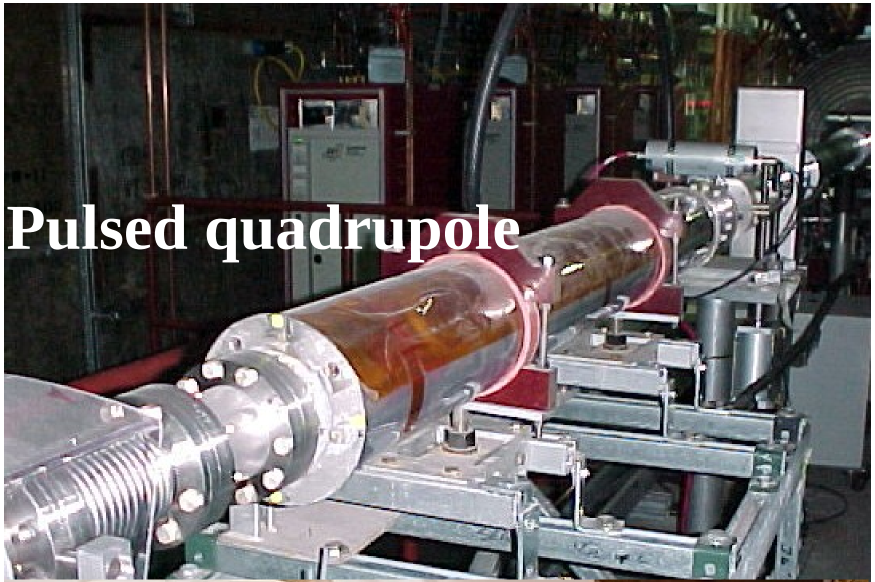
Pulsed quadrupole in RHIC

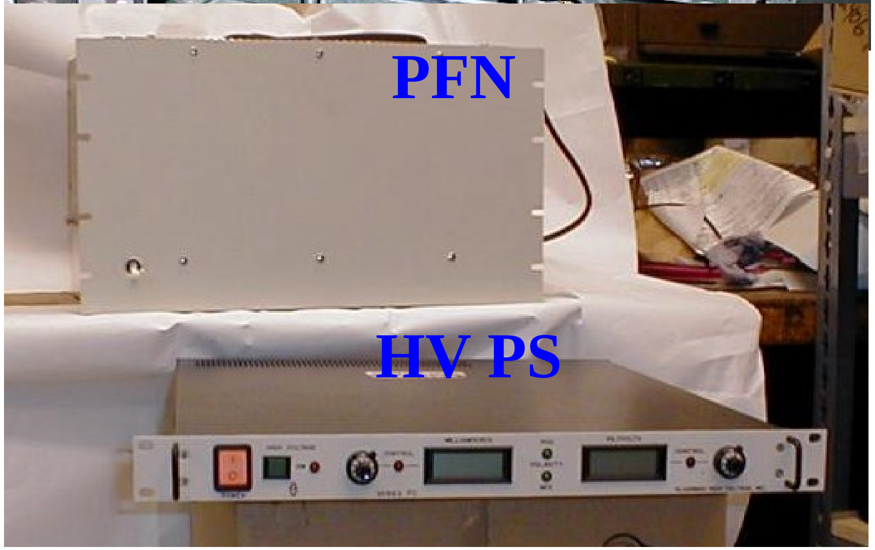
Air core magnet

(Tevatron slow extraction)

Length l	1.5 m
Transfer B/I	3.6 T/kA
Inductance L	105 μH
Current I	50 A
Voltage U	2 kV
Rise and fall time	13 μs (1 turn)

Parameter set is for a quadrupole strength of $k = 0.002/\text{m}$ ($f = 500\text{m}$).



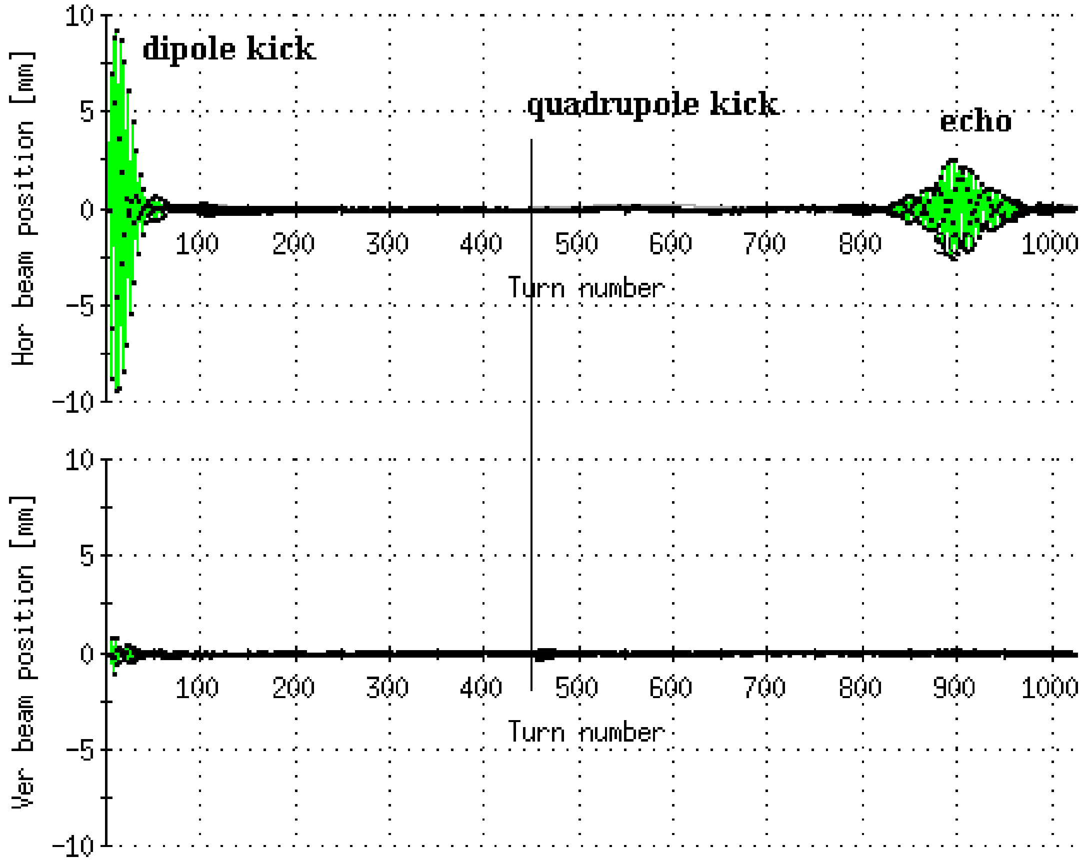


[W. Fischer, A. Jain, D. Trbojevic, “The AC quadrupole in RHIC”, BNL RHIC/AP/165 (1999).
O. Dressler, “Quadrupole kicker for RHIC”, BNL C-A/AP/60 (2001), J. Addessi, J. Piacentino, D. Warburton]

RHIC transverse echoes (1)

First RHIC echoes

- Au^{79+} at injection
- single bunch
- dipole kick by injecting with angle
- 1-turn quad kick



[W. Fischer, R. Tomas, T. Satogata, **PAC05]**

RHIC transverse echoes (2)

Can observe echoes only

- With dipole kick of a few σ

- Nonlinear detuning an order of magnitude larger than natural one

- Quadrupole kick times no larger than a few 100 turns

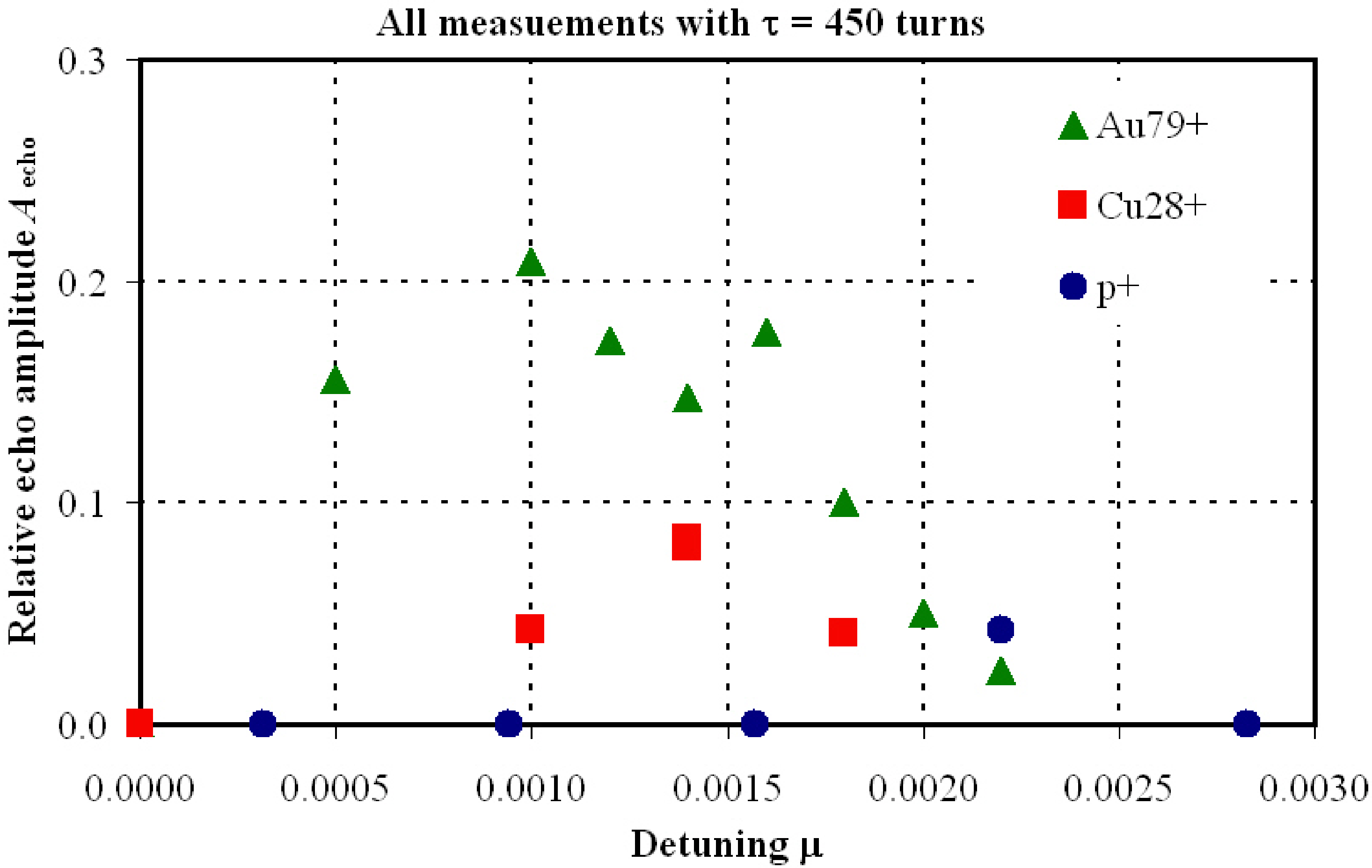
RHIC transverse echoes (3)

TABLE 1. Typical parameters for transverse echo measurement in RHIC with beams of gold and copper ions, and protons.

parameter	unit	Au	Cu	p
mass and charge number A, Z	...	197, 79	63,29	1,1
relativistic γ	...	10.5	12.1	25.9
revolution time T_0	μs		12.8	
rms emittance, unnorm. ε	mm·mrad	0.16		0.10
detuning μ	...		0.0014	
decoherence time τ_d	turns		57	
dipole kick a	mm / σ		10 / $\approx$ 4	
normalized quadrupole kick Q	...		0.025	
time τ_0	turns		10	
quadrupole kick time τ	turns	450		200
synchrotron period T_s	turns	450	540	3900
bunch intensity N_b	10^9	0.1–1.0	0.1–1.3	65–95

RHIC transverse echoes (4)

Scan of nonlinear detuning μ (octupoles)

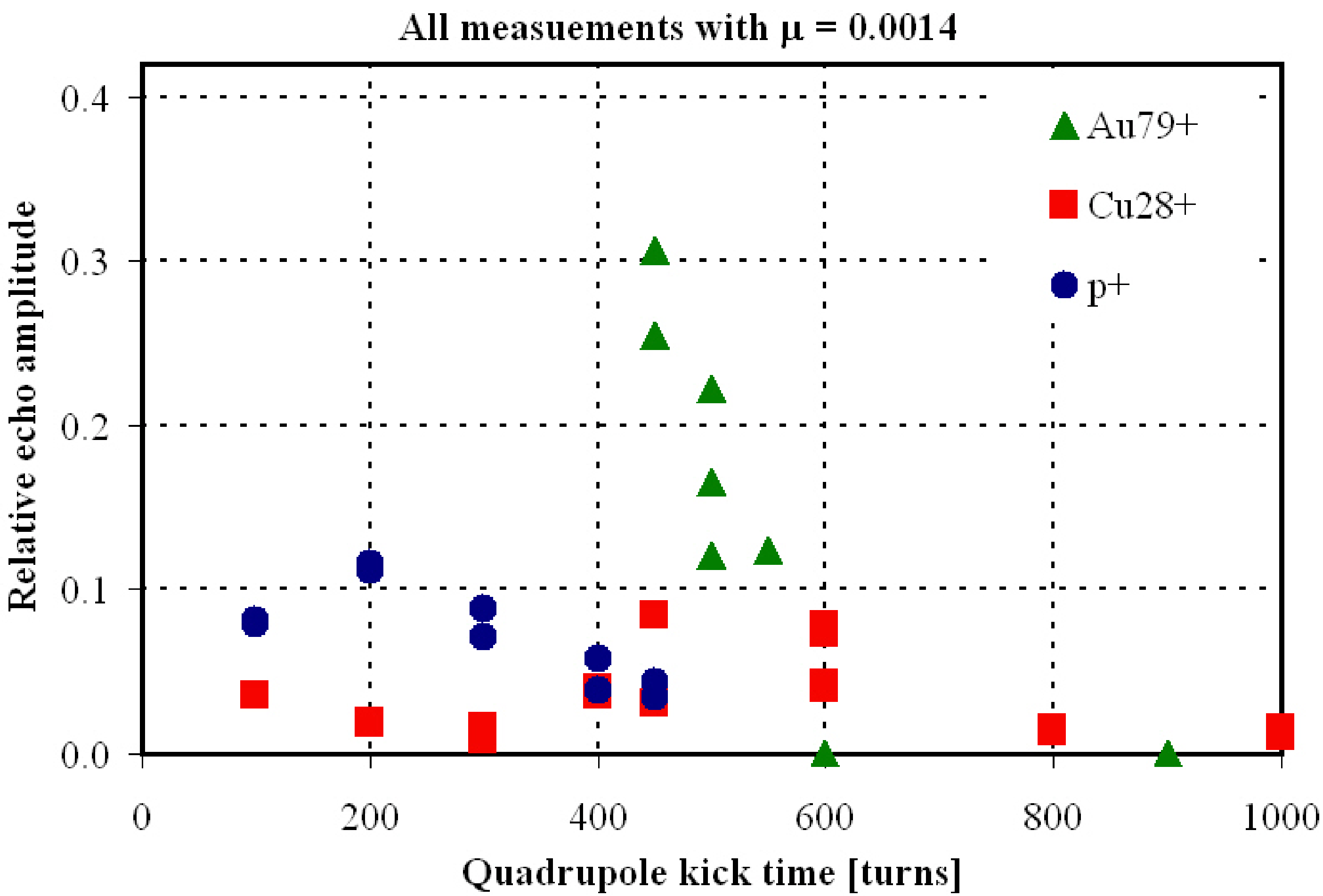


- no echo without detuning, no echo with large detuning

- very weak proton echoes (unexpected)

RHIC transverse echoes (5)

Scan of quadrupole kick time τ

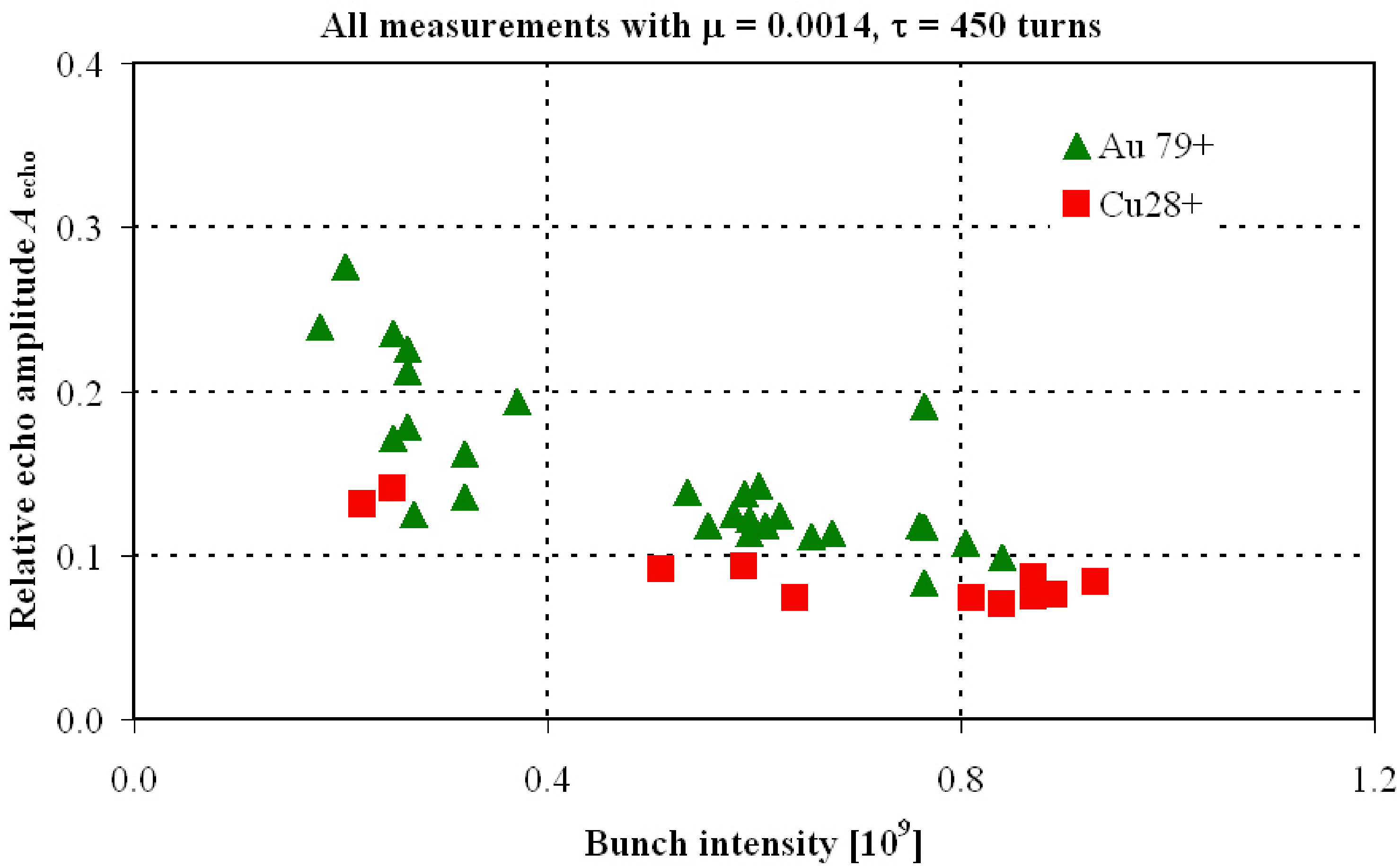


- no echo small τ, no echo with large τ

- very weak proton echoes (unexpected)

RHIC transverse echoes (6)

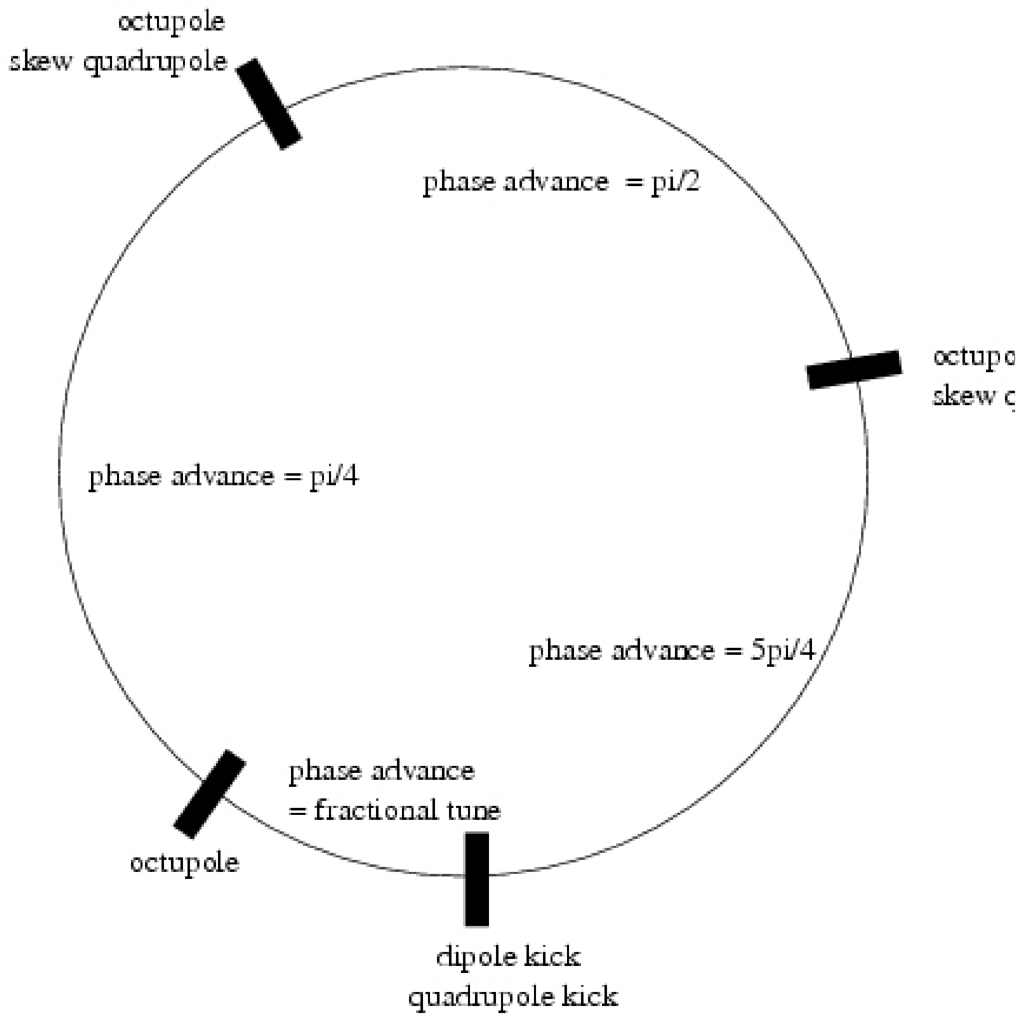
Scan of bunch intensity N_b (increasing diffusion from IBS)



- echo decreases with increasing bunch intensity (like IBS)

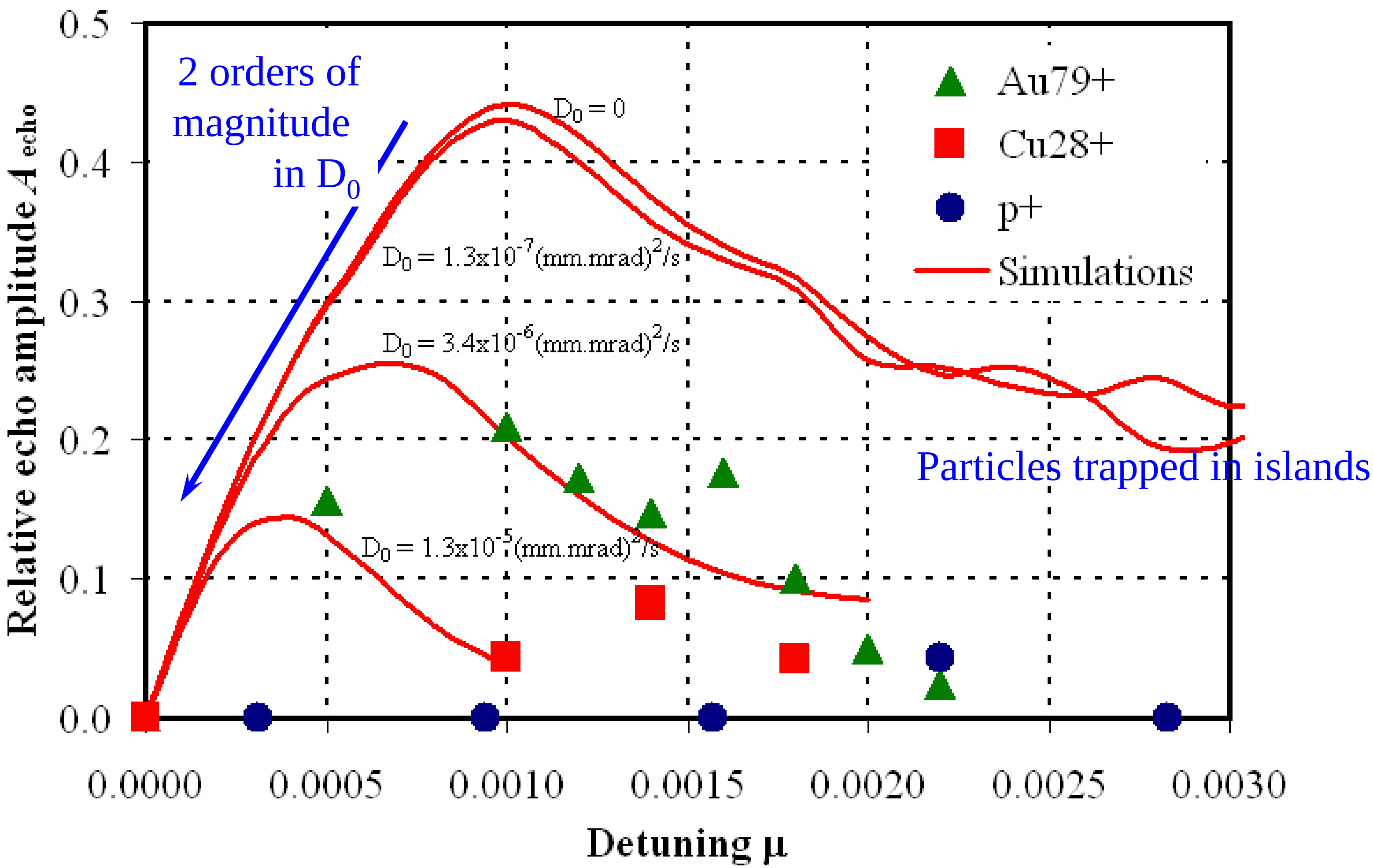
- no proton data over sufficiently large range of N_b

Simulations (1)



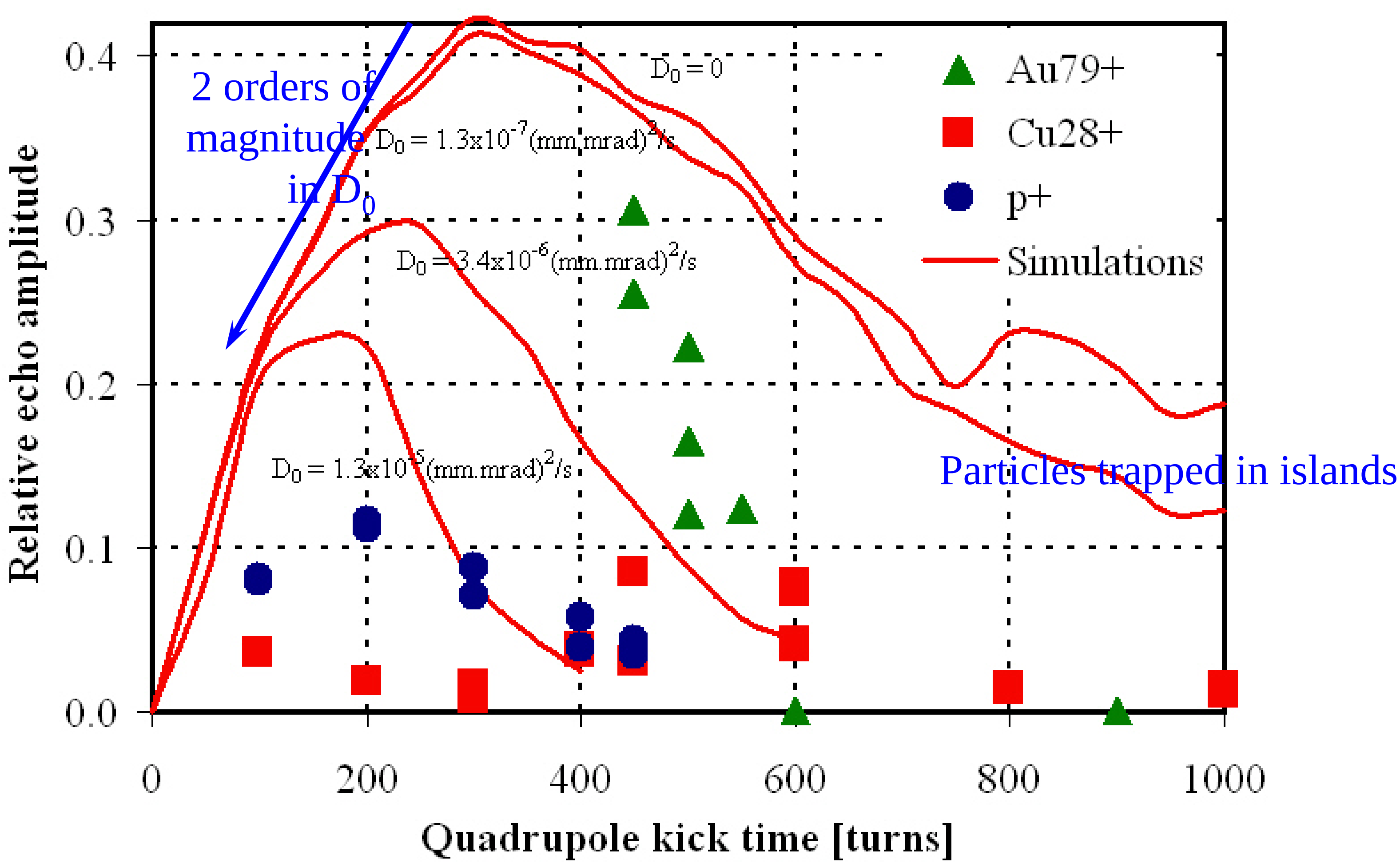
- only 1D **(now 2D)**
- linear transfer matrixes
- octupoles to adjust μ
- typically 10000 particles
- diffusion introduced through random kicks from Gaussian distribution (adjustable width, constant for all amplitudes)

Simulations (2)



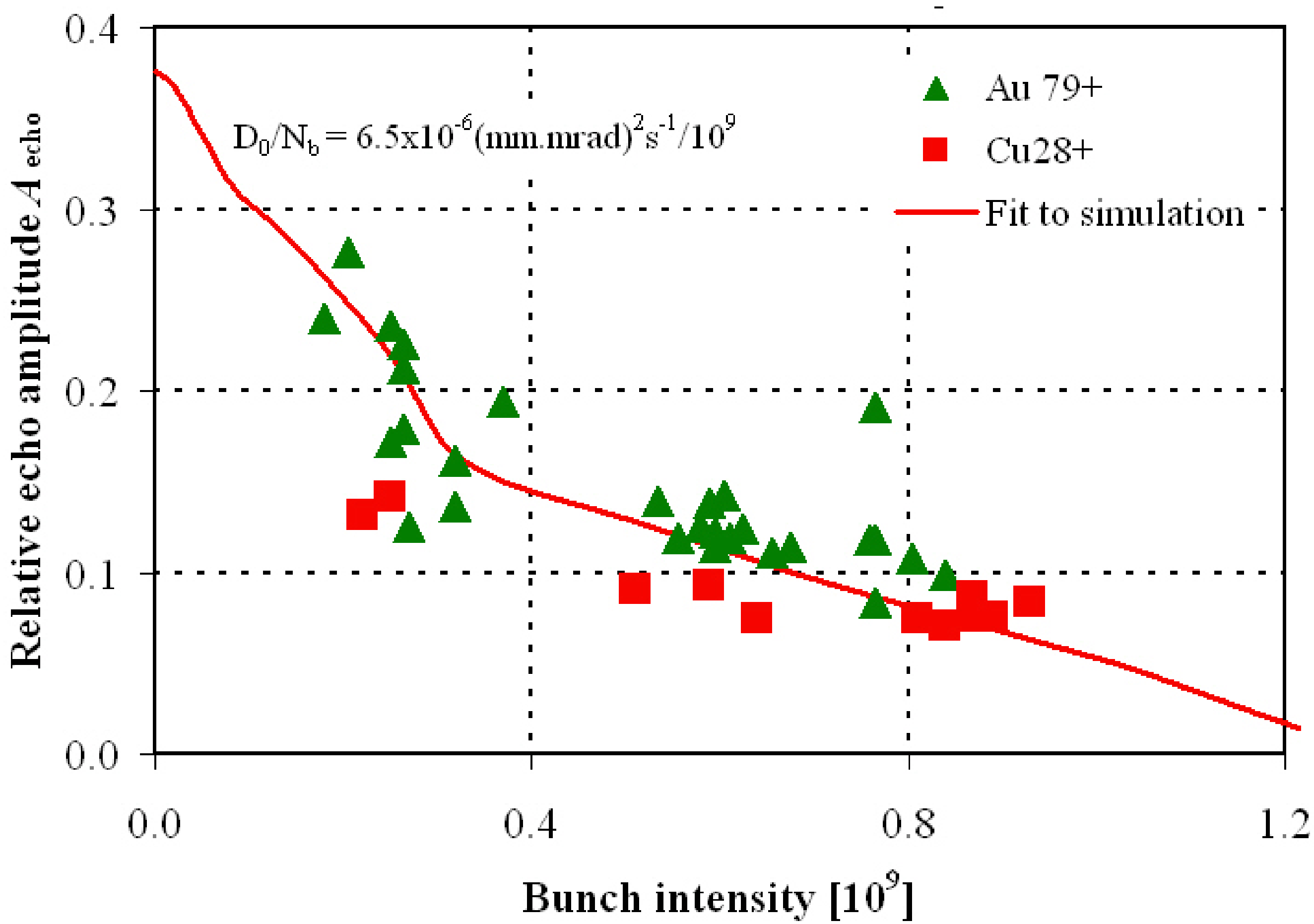
Can find diffusion coefficient in simulation that approximately reproduces detuning scan for gold ions

Simulation (3)



Simulation can reproduce experimental main features of experimental quadrupole kick time scan

Simulation (4)



Expect IBS growth rates for Cu about factor 2 smaller than those for Au

- **Can find proportionality coefficient D_0/N_b so that simulation fits experimental intensity dependency (→ extracts measured D_0)**
- **Fitted D_0 corresponds to emittance growth time of about 100 h, consistent with free expansion measurements (not very accurate)**

Summary – Transverse Echoes in RHIC

- Transverse echoes observed in RHIC with Au^{79+}, Cu^{29+}, p^{+}
  - Dipole kick with injection under angle
  - Air core quadrupole provides 1-turn kick
- Diffusion with p^{+} stronger than with heavier ions (unexpected)
- Observed intensity dependent echoes with Au^{79+}, Cu^{29+},
  $\rightarrow$ were fitted to simulation results to extract diffusion rates